Short-pulse and high-repetition-rate diode-pumped Yb:CaF2 regenerative amplifier

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Abstract: We present a diode-pumped regenerative amplifier based on an $Yb:CaF_2$ crystal optimized to produce short pulses for various repetition rates ranging from 100 Hz to 10 kHz. The shortest pulse duration generated is 178-fs, and the corresponding energy is 1.4 mJ before compression (620 µJ after), at a repetition rate of 500 Hz for 16 W of pump power. The bandwidth is 10 nm centered at 1040 nm. Higher repetition rate regimes have also been explored allowing an optical-optical efficiency up to 10% at high repetition rate.

OCIS codes: 140.3280, 140.3380, 140.3480, 140.3615, 140.7090.

More and more industrial applications require reliable, efficient and compact laser configurations. From this point of view, due to their favorable spectroscopic and thermal properties, diode-pumped systems based on ytterbium-doped crystals are now very popular for the production of high energy and ultra-short laser pulses.

Many research efforts have been devoted to the generation of short and energetic pulses both in oscillator and amplifier setups based on these Ytterbium-doped crystals. Within oscillators, ultra-short pulses (down to 47 fs with Yb:CALGO [1]) or high average powers (80 W) [2] combined with energetic laser pulses (25 µJ with Yb:YAG in thin disk structures) have been obtained. Nevertheless, for energies above the mJ range, regenerative amplifiers are required, but a compromise between high average power and short pulse duration is necessary. To overcome the limited available bandwidth, one method consists of combining gain media with slightly shifted but overlapping bandwidths, as in the regenerative thin-disk Yb:KYW amplifier presented in ref. 3 (500 µJ sub 200 fs pulses). Investigating new materials is another approach to access broad gain spectra and generate shorter and more energetic pulses.

Recently, a “new-old” [4] laser material demonstrated very promising results for short and energetic pulse generation. Indeed, Yb:CaF_2 offers good thermal properties (thermal conductivity of 9.7 W m^{-1} K^{-1} for undoped material [5] and still around 5.0 W m^{-1} K^{-1} for 5-at. .% doping level [6]), together with broad emission and absorption bands due to the particular arrangement of the Yb^{3+} ions in the structure of CaF_2 [4]. Furthermore, Yb:CaF_2 has a long fluorescence lifetime of 2.4 ms [5], indicating high energy storage capacity, and therefore allowing the generation of energetic pulses at repetition rates in the 100 Hz range.

So far, these properties have been exploited in the context of diode-pumped systems in an ultrashort oscillator producing sub-100 fs pulses [7] and in a very high energy TW amplifier [8]. This TW system generates 197 mJ, 192 fs pulses at low repetition rate (1 Hz), and with an optical-to optical conversion efficiency of 1.4 %. Codoped Yb^{3+}, Na^{+}:CaF_2 has also been used in a cryogenically cooled regenerative amplifier [9]. In this work, pulses at a repetition rate of 1 kHz are generated, with an energy of 3 mJ before compression (optical-to-optical conversion efficiency of 3.1%), and a duration of 195 fs after compression. However, Na codoping seems to lead to several differences compared to Yb:CaF_2 such as a lower thermal conductivity, a more structured emission spectrum and a longer lifetime.

In this paper we present a room-temperature diode-pumped regenerative amplifier based on a singly doped Yb:CaF_2 single crystal, allowing the generation of mJ sub-200 fs pulses with a high conversion efficiency. The limitations in terms of pulse duration of Yb:CaF_2 amplifiers versus repetition rate are examined. For that, we investigate the influence of gain shaping in Q-switched and injected regimes, as a function of repetition rate.

The experiment is performed with a 2.6-% Yb doped 5-mm-long Brewster-cut CaF_2 crystal grown by using the Bridgman technique. The experimental setup, and particularly the regenerative amplifier, is illustrated in fig. 1. The crystal is in a copper mount. To optimize the injection pulse spectrum in terms of bandwidth and maximum gain, the seed pulses are generated by a broadband Yb:CALGO oscillator centered at 1043 nm with a FWHM bandwidth of 15 nm (fig. 2) at a repetition rate of 27 MHz [10]. The pulses are stretched to 260 ps with a transmission grating (1600 l/mm). The regenerative amplifier contains a thin-film polarizer (TFP) and a BBO Pockels cell (PC) for polarization switching and hence injecting and extracting the oscillator pulses and the amplified pulses, respectively. The amplifier crystal is longitudinally pumped through a dichroic mirror using a 16-W 200-µm (N.A. 0.22)-fiber-coupled laser diode emitting at 980 nm. Thanks to the broad absorption band of the crystal, the emission wavelength of the laser diode does not need any stabilization with Bragg gratings. To optimize the overlap between the laser and the pump beams, the diode is collimated and focused by two 50 mm focal-length triplets to reduce optical aberrations. The cavity is designed in order to obtain diffraction limited laser beam at the output, with a cavity length of about 1.5 m. The Pockels cell is adjusted to act as a quarter wave plate at 45° in static state, i.e. without high voltage, and as a half wave plate with quarter wave voltage applied to the electrodes. Between the stretcher and the amplifier, a TFP, a Faraday rotator (FR) and a half-wave plate are placed in order to separate input and output beam. Finally, after a beam expander, the chirped pulses are compressed using two transmission gratings (1600 l/mm), with an overall efficiency of 45 %.

Yb:CaF_2 spectral gain depends on the population inversion level – as for all Yb-doped gain media – due to the interplay between reabsorption and stimulated emission. This results, in a maximum gain around 1045 nm for low inversion rate and around 1035 nm for high inversion rate. In Q-switched operation, it is possible to balance these two peaks in order to obtain broad spectra. At 100 Hz, for example, a bandwidth of 16 nm FWHM can be obtained with a "camel" shape transcribing the valley at 1040 nm observable in the spectral gain profile. In this case the nanosecond pulses have an energy of 1.8 mJ.

In the regenerative amplifier configuration, we also notice spectral shaping effects as a function of the repetition rate due to the relationship between the population inversion and the gain in Yb-doped material. For high repetition rates (lower inversion levels) the spectrum exhibits a red shift. This effect is also observed at fixed repetition rate, as shown in fig. 2, by slightly changing the extraction time. It is therefore possible to obtain a broad spectrum for repetition rates below 1 kHz. Above this value, the pulse duration increases due to the low inversion-induced red-shift as shown in fig. 3. For example, the shortest pulse duration at 10 kHz is 400 fs with a 7.3 nm-bandwidth spectrum centered at 1045 nm.

Generally, at lower repetition rate the amplified pulses are broader, and the shortest pulses obtained have a spectral bandwidth between 10 and 15 nm FWHM. The short pulse regime is typically accessible between few Hz up to the kHz, with the shortest pulses obtained at 500

Hz repetition rate. The pulse duration in this case, measured both by frequency-resolved optical gating (SHG-FROG) and autocorrelation is 178 fs. The input spectrum (centered at 1043 nm) is slightly blue shifted to 1040 nm, and the amplified pulse spectrum has a bandwidth of 10 nm (fig. 4). The energies before and after compression are respectively 1.4 mJ and 620 µJ with optical-to-optical efficiency of 4.4% (before compression), which leads, taking into account a pump absorption of 62%, to a laser/absorbed-pump-power efficiency of 7%. As shown in fig. 1, the beam profile exhibits a Gaussian shape, with $M^2 < 1.1$ in both vertical and horizontal directions.

As mentioned before and shown in fig. 2, broader spectra are also accessible in this low repetition rate regime. Nevertheless, these broadband spectra do not correspond to the shortest pulses since we were unable to compress them to the transform-limit. For example, at 500 Hz repetition rate, for a 14-nm-broad spectrum the compressed pulse durations is 200 fs. As confirmed by our FROG measurements, this incomplete compression is due to remaining high order phase distortions.

In figure 5 the output energy of the amplifier is ploted against the repetition rate. The maximum energy plateau occurs at a repetition rate below 300 Hz (fig. 5) which is in agreement with the lifetime of 2.4 ms of Yb:CaF_2. The maximum pulse energy is 1.6 mJ /700 µJ (uncompressed/compressed) corresponding to 130 roundtrips.

At high repetition rate, typically 10 kHz, the output energy is strongly reduced while an average power as high as 1.4 W before compression (0.6 W after) is obtained. This corresponds to an optical-optical efficiency of 9 % (before compression) due to the absorption increase to 72%, and a laser/absorbed-pump-power efficiency of 12 %. For comparison, in cw regime we have obtained up to 13 % of optical-to-optical efficiency.

In conclusion, we have demonstrated a diode-pumped room-temperature regenerative Yb:CaF_2 amplifier operating at high repetition rate. Seeded with pulses from an Yb: CALGO oscillator, this amplifier delivers short pulses (≈180 fs) at up to 1 kHz repetition rate. The maximum extracted energy is 1.6 mJ/0.7 mJ (before / after compression). The highest average power is 1.4 W/0.6 W (before / after compression) corresponding to an optical efficiency around 10 %. The bandwidth of the output pulses shows potential for sub-100 fs pulses if high order phase distortion is controlled. Furthermore considering the good thermal properties of the crystal, one can expect to obtain higher average power at high repetition rates thanks to higher pumping, moreover, using a cryogenically cooled crystal should really scale up the average power of the amplifier.

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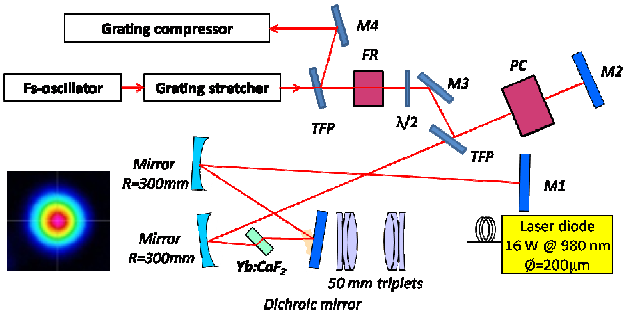
Fig. 1. Experimental setup: M1, M2, M3 and M4, plane HR mirrors; FR, Faraday Rotator; PC, Pockels Cell. M1-R300: 600mm; R300-Crystal: 170mm; Crystal-R300: 165mm; R300-M2: 500mm. Inset, profile of the 1.4 mJ 500 Hz output beam.

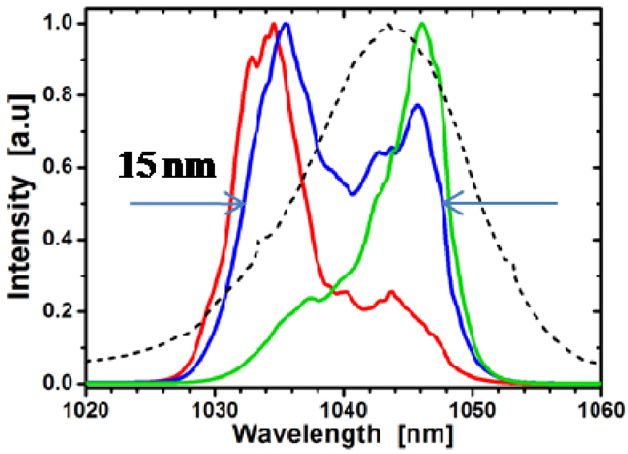
Fig. 2. Evolution of the spectrum of the amplified pulse at 500 Hz repetition rate for different time of extraction: 1.35 µs, 300 µJ (red curve), 1.7 µs, 620 µJ (blue curve), 2.2 µs, 580 µJ (green curve). Short dash curve corresponds to the oscillator spectrum.

Fig. 3. Evolution of pulse duration after compression vs repetition rate.

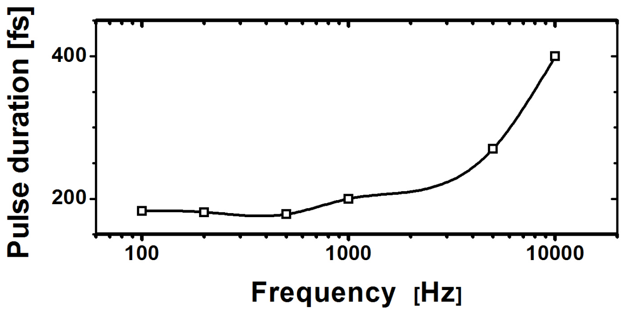
Fig. 4. Recompressed pulse measurement with SHG FROG for output energy of 620 µJ at a repetition rate of 500 Hz.

Fig. 5. Evolution of output pulse energy and average power after compression vs repetition rate.

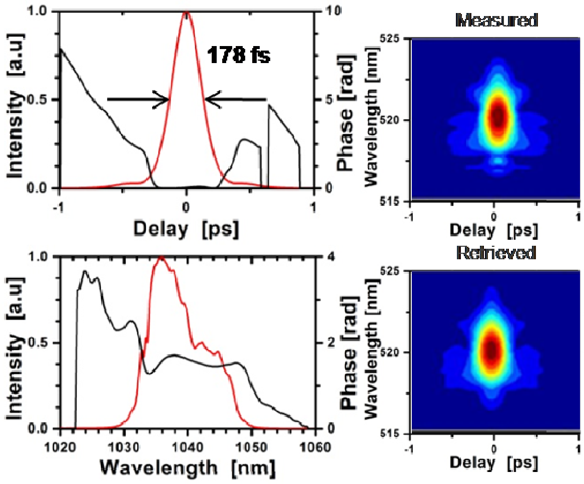

Grating compressor
M4
FR
Fs-oscillator
Grating stretcher
TFP
λ/2
M3
PC
M2
TFP
Mirror
R=300mm
M1
Mirror
R=300mm
Yb:CaF2
Laser diode
16 W @ 980 nm
Ø=200µm
50 mm triplets
Dichroic mirror



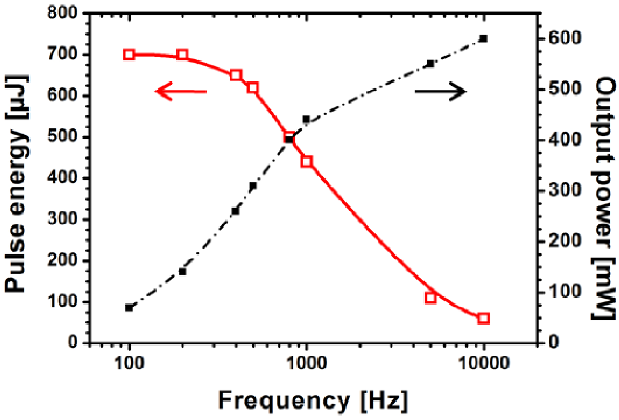
15 nm
Intensity [a.u]
Wavelength [nm]
0.0
0.2
0.4
0.6
0.8
1.0
1020
1030
1040
1050
1060



Pulse duration [fs]
400
200
100
1000
10000
Frequency [Hz]



178 fs
Intensity [a.u]
Phase [rad]
Delay [ps]
Measured
Retrieved
Wavelength [nm]
Wavelength [nm]



Pulse energy [μJ]
Output power [mW]
Frequency [Hz]
0
100
200
300
400
500
600
700
800
100
1000
10000